Naturally commutated thyristor-controlled high-pulse VAr compensator

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Abstract: An alternative to the thyristor controlled reactor is proposed based on the ability of the AC/DC convertor to absorb controllable reactive power. The standard three-phase bridge configuration is modified, using the concept of DC ripple reinjection, to achieve high pulse operation without the need for passive harmonic filtering. A 36-pulse scaled-down test system is used to verify the theoretical predictions.

1 Introduction

Controllable static VAr compensation (SVC) is the main field of application of the fast developing FACTS technology [1]. Much of the SVC development has centred on the thyristor-controlled reactor (TCR) [2]. While this equipment provides an acceptable solution to the problem, the search for alternatives continues to reduce cost and/or improve the technical performance.

A possible alternative is the use of an AC/DC convertor as a controllable sink of reactive power [3]. In common with early compensators, such as the synchronous condenser and saturable reactor, the AC/DC convertor has inherent short-term overvoltage control capability; an important feature in the dynamic performance of power systems. The TCR also can be designed with such capability if the nominal operating point is obtained at an increased firing angle (i.e. greater than 90°); this, however, implies a substantial increase in harmonic content in the normal operating region. The harmonic content of an AC/DC naturally commutated VAr compensator is dependent on the pulse number and on the amount of compensation required. There is, therefore, considerable interest in raising the pulse number beyond the conventional twelve pulses. This could be achieved with a multiple-bridge configuration, each bridge being supplied by a complex zig-zag transformer connection to perform the harmonic cancellation. A more effective way of increasing the number of pulses has been proposed for use in HVDC using the DC ripple reinjection scheme [4, 5]. The same technique is used in this paper to produce a filterless AC/DC VAr compensator.

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2 Double bridge rectifier as a VAr compensator

The convertor configuration of Fig. 1*a* constitutes a 12-pulse naturally commutated static VAr compensator. A laboratory model of this configuration has been used to

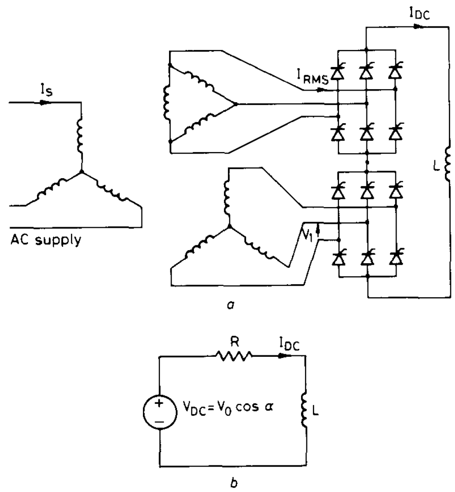

Fig. 1 *12-pulse naturally commutated SVC*

derive the relationships between reactive power (Q), DC current (I_{DC}) and harmonic content for different firing angles and the results are plotted in Fig. 2.

The linear characteristic of I_{DC} versus firing angle is easily explained if the convertor is modelled as shown in Fig. 1*b*. The model consists of a DC voltage source (V_{DC}) with a value V_0 cos α (where V_0 is the maximum average DC voltage), a smoothing reactor (L) and a small effective resistance (R). As the resistance is very small, the steady state average DC voltage must also be small in order to limit the average DC current; this is achieved when the firing angle is near 90°. In this region the cosine function, and thus the DC voltage and current, can be assumed to vary linearly with the firing angle. The ideal

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AC supply current (I_s) waveform for the 12-pulse naturally commutated SVC and its harmonic content are shown in Fig. 3. The measured harmonics in Fig. 2 approach these ideal values as the firing angle gets close to 90°. This is because the current reduces to zero as the firing angle approaches 90° and the commutation interval becomes negligible [6].

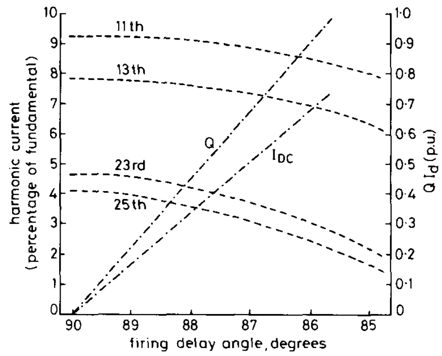

Fig. 2 *Characteristic of the 12-pulse static convertor as an SVC*

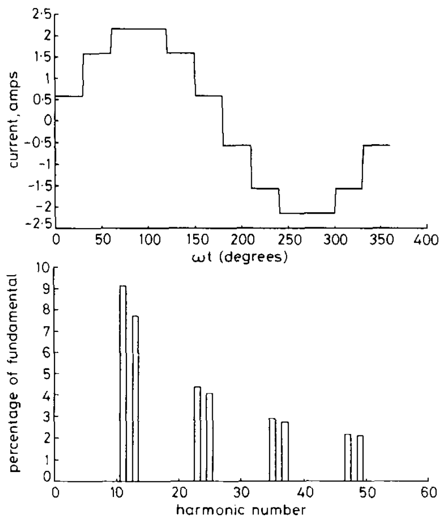

Fig. 3 *Ideal 12-pulse AC current waveform and harmonic content*

3 High pulse naturally commutated VAr compensation

Fig. 4 shows a double bridge configuration modified with a DC current reinjection circuit that changes the 12-pulse conversion into 36-pulses. The reinjection scheme consists of two capacitors (C_1 and C_2) which block the DC component of the 12-pulse convertor DC voltage, two reinjection transformers (T_{RJ1} and T_{RJ2}) and a single-phase fully controlled naturally commutated bridge with a bypass switch. The latter periodically redirects the flow of DC current into the reinjection transformers in such a way as to produce a rectangular waveform (I_{RJ}) at six times the fundamental frequency (Fig. 5*a*). This current, scaled by the reinjection transformer ratio, is injected into the main convertor transformer via the thyristor bridges.

The ideal waveforms shown in Fig. 5*b*, *c* and *d* show the conventional 12-pulse waveforms drawn in solid lines, while the dotted lines represent the changes to the waveforms because of the reinjected current. In Fig. 5*b* and *c* the ideal currents in the secondary windings of the main transformer are shown. When these currents are added the AC supply current (I_s) is formed, as shown in Fig. 5*d*. As the single phase bridge is connected in series with the twelve-pulse bridge, the resulting DC voltage across the reactor (L) exhibits 36-pulse ripple.

4 Test system

A 2.6 kVAr hardware model of the 36-pulse naturally commutated SVC has been constructed. Scaling down of the power components presents several problems, the main one being the presence of a significant magnetising current, and therefore harmonic content, in the model transformers. The problem was alleviated by operating the model at 80% rated voltage, to reduce the level of saturation in the transformer and with it the magnetising current harmonics.

Additionally, compared to typical power system transformers, the model transformer has a smaller percentage reactance and larger percentage resistance. The reactance values have been increased by adding reactance in series. The values used for the DC reactor ($L = 2.8$ mH) and

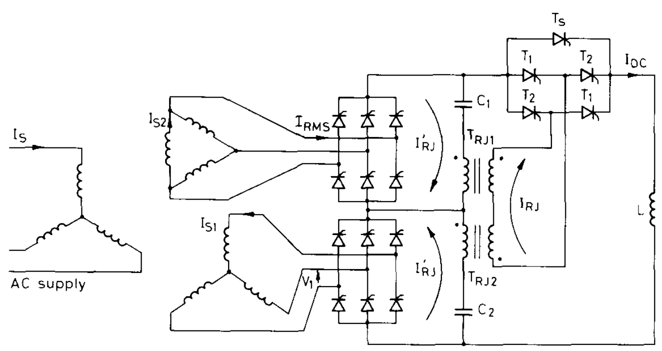

Fig. 4 *36-pulse naturally commutated SVC circuit*

blocking capacitors ($C = 1500\ \mu F$) were derived with the criteria discussed in Section 6.

4.1 Controller

In synchronism with the AC voltage the correct combination of main and reinjection bridge thyristors must be fired at regular intervals, 36 times per AC cycle. In other words, thyristors are fired every 10°. Fig. 6 illustrates the firing synchronisation of the reinjection bridge and the main bridges. The reinjection bridge has three states, defined by the condition of thyristors T_s, T_1 or T_2. The conduction of T_s means that the reinjection transformer is bypassed, which occurs in the middle of every main bridge conduction state. For example, T_s is fired 10° after the main bridge changes state and conducts for 10°. For the remainder of the time either T_1 or T_2 conduct.

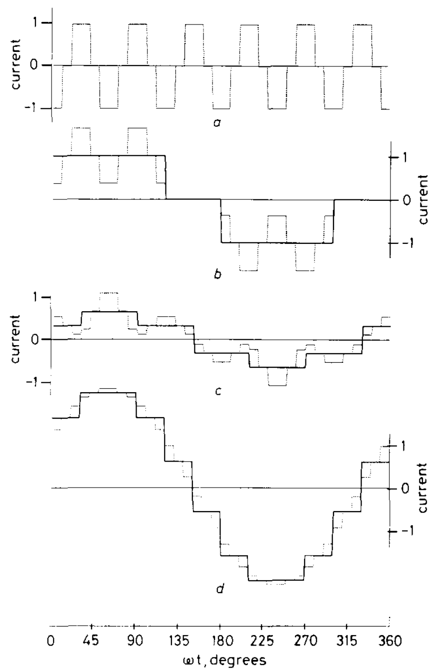

Fig. 5 *Ideal current waveforms within the 36-pulse naturally commutated SVC*

a Reinjected current, I_{aj}
b Current in the star secondary winding, I_{s1}
c Current in the delta secondary winding, I_{s2}
d AC supply current ($I_s = [N_1/N_0][I_{s1} + \sqrt{(3)}I_{s2}]$)
Note: DC current = 1 A, transformer ratio, $N_1/N_0 = 1$

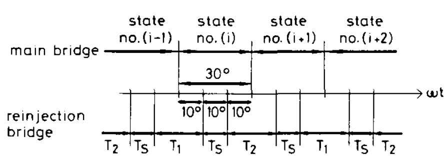

Fig. 6 *Main and reinjection bridge thyristor firing pattern*

The firing controller was developed using a digital signal processor (DSP) system. This system uses a TMS 320C30 processor, which is characterised by a 32-bit data bus, 60 ns instruction period and floating point arithmetic hardware.

As well as precise timing for the firing of the thyristors, this processor permits the implementation of complex control algorithms. For example, the DSP could be used to monitor the AC current harmonic content and adjust the control to minimise it.

Essentially the controller consists of two phase lock loops (PLL), as shown in Fig. 7, which receive the firing angle command and generate the appropriate timing signals for the thyristor drivers. PLL 1 locks onto the AC voltage frequency thus generating a filtered timing representation of that voltage within the DSP. PLL 2 automatically operates at the same frequency as PLL 1, but incorporates a phase delay specified by the firing angle command and frequency multiplier to provide 36 pulses per AC cycle.

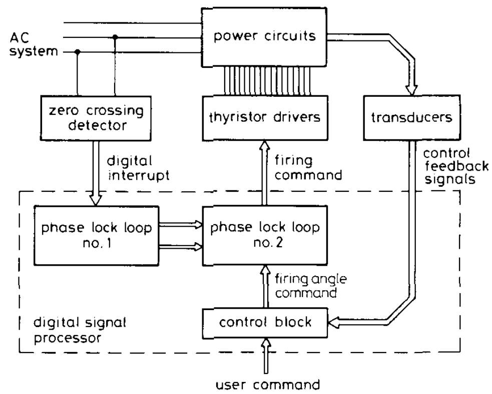

Fig. 7 *Controller for the naturally commutated SVC*

5 Illustrative results

The reactive power absorbed by the test system was adjustable from 0.26 kVAr (at $\alpha = 89°$) to the full 2.6 kVAr (at $\alpha = 80°$). The variation of reactive power with firing angle for the 36-pulse convertor is the same as for the 12-pulse configuration, i.e. the characteristics for I_{DC} and Q of Fig. 2 still apply.

The relatively large variation of firing angle is due to the unrealistically high value of the test system resistance. In a high voltage scheme the firing angle for maximum power should be much closer to 90°. To verify the theoretical predictions illustrated in Fig. 5, corresponding current waveforms measured on the transformer secondaries of neutral voltage and phase current waveforms, shown in Fig. 8*a* give an idea of total distortion and phase angle displacement (approximately 90°).

The main difference between the ideal and experimental waveforms is the slopes of the current transitions due to the commutation process, which also shows some asymmetry between main and reinjection bridge commutations.

With ideal 36-pulse operation the harmonic orders below the 35th are absent and the levels of the 35th and 37th are inversely proportional to the harmonic order. However, the 36-pulse related harmonics of the experimental waveform (Fig. 9) are slightly lower than the ideal as a result of the commutation overlaps. Moreover, the experimental spectrum contains small amounts of all harmonic orders, particularly the 6-pulse related, which are predominantly due to

(i) construction imperfections affecting the reinjection transformer turns ratio

(ii) nonlinearity of the magnetising characteristic of the main transformer

(iii) asymmetries in the AC supply voltages, main transformer leakage reactances, control firings etc.

Finally, the test system variation of harmonic content with load (summarised in terms of firing angle) is shown in fig. 10; in this case the magnitude of the harmonics are specified relative to the full load fundamental component.

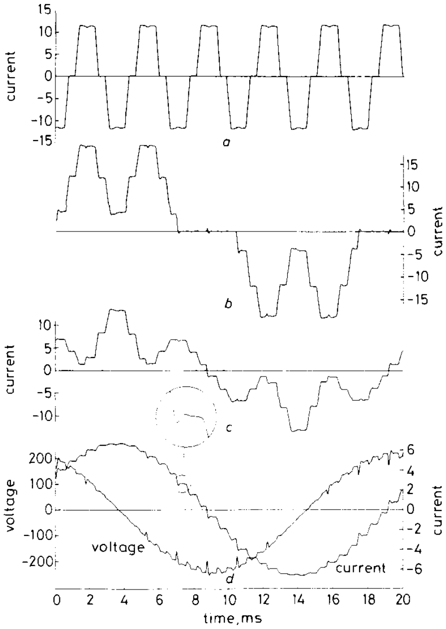

Fig. 8 *Experimental supply current and voltage waveform*

a Reinjected current, I_{aj}
b Current in the star secondary winding, I_{s1}
c Current in the delta secondary winding, I_{s2}
d AC supply current ($I_s = [N_1/N_0][I_{s1} + \sqrt{(3)}I_{s2}]$)
Note: DC current = 12 A, transformer ratio, $N_1/N_0 = 4$

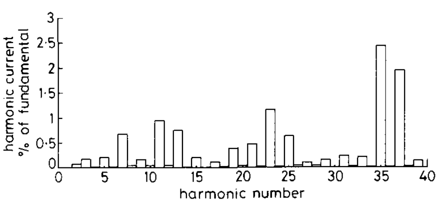

Fig. 9 *Harmonic content of the experimental supply current waveform*

6 A comparison of component ratings

Three topologies considered in the ratings comparison are the TCR, the 12-pulse naturally commutated SVC and the 36-pulse naturally commutated SVC. Each of the three topologies uses the same 3-phase transformer configuration with a secondary voltage of V_1. The reactive power rating, in terms of the ratings at the transformer secondary, is

$$Q = 6\left(\frac{V_1}{\sqrt{3}}\right)I_{RMS(F)} \tag{1}$$

where $I_{RMS(F)}$ is the rated fundamental phase current. In the equations that follow all current, voltage, active

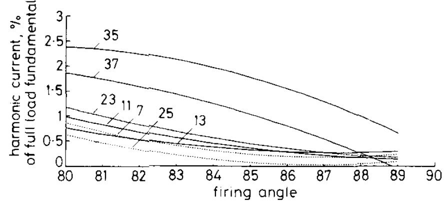

Fig. 10 *Experimental supply current harmonics over the operating range of the SVC*

power, inductance and capacitance ratings will be normalised with reference to $I_{RMS(F)}$, V_1, Q, $(V_1^2/\omega Q)$ and $(Q/\omega V_1^2)$, respectively. The main results from this comparison are summarised in Table 1.

6.1 Main transformer

The VA ratings of the 3-phase transformer, in terms of the ratings at the transformer secondary, is expressed as

$$S = 6\left(\frac{V_1}{\sqrt{3}}\right)I_{RMS} = \left(\frac{I_{RMS}}{I_{RMS(F)}}\right)Q \tag{2}$$

where I_{RMS} is rated RMS phase current. In the case of the TCR, at rated power, the phase currents are sinusoidal (i.e. $I_{RMS} = I_{RMS(F)}$) and, therefore, the normalised VA rating is 1. For the 12-pulse naturally commutated SVC the theoretical values of I_{RMS} and $I_{RMS(F)}$ are $0.817I_{DC}$ and $0.780I_{DC}$, respectively, giving a normalised VA rating of 1.05. The 36-pulse naturally commutated SVC with theoretical values for I_{RMS} and $I_{RMS(F)}$ of $0.927I_{DC}$ and $0.795I_{DC}$ respectively, give a normalised rating 1.17.

6.2 Main thyristors

In all three cases the peak reverse voltage experienced by the main thyristors is $\sqrt{(2)}V_1$. Because I_{RMS} is the rated RMS phase current at the transformer secondary and the thyristor/reactor units of the TCR are connected in a delta configuration, the thyristor current is $1/(\sqrt{(2)}\sqrt{(3)})$. Similarly the normalised average thyristor current is $\sqrt{(2)}/(\sqrt{(3)}\pi)$.

Considering the AC/DC conversion alternatives, the RMS current in the main bridge thyristors is $I_{RMS}/\sqrt{(2)}$ and the average current $I_{DC}/3$, which after substitution and normalisation give the following RMS and average values of thyristor current:

$$\text{12-pulse configuration} \quad \frac{0.817}{0.780\sqrt{2}} \quad \text{and} \quad \frac{1}{0.780 \times 3}$$

$$\text{36-pulse configuration} \quad \frac{0.927}{0.795\sqrt{2}} \quad \text{and} \quad \frac{1}{0.795 \times 3}$$

6.3 Reactors

The inductance of the DC reactor influences the harmonic distribution of the DC and AC currents, and the

Table 1 : Normalised component rating summary

	12-pulse TCR	12-pulse NC-SVC	36-pulse NC-SVC
3 phase transformer			
VA rating	1	1.05	1.17
Main thyristors			
Number	12	12	12
Peak reverse voltage	1.41	1.41	1.41
RMS current	0.408	0.741	0.825
Average current	0.260	0.427	0.419
Reactors			
Number	6	1	1
Inductance value	6	3.4	0.38
Current rating (RMS)	0.577	1.28	1.26
Reinjection thyristors			
Number	not applicable	not applicable	5
Peak reverse voltage			0.482
RMS current			0.726
Average current			0.419
Reinj. transformers			
Number	not applicable	not applicable	2
VA rating			0.071
Reinj. capacitors			
Number	not applicable	not applicable	2
Capacitance value			1.14
Filters	small	large	not needed

The normalising factors are: current $I_{RMS(F)}$, voltage V_1, power Q, inductance $V_1^2/\omega Q$, capacitance $Q/\omega V_1^2$

dynamic characteristics of the compensator. This paper is discussing the steady state characteristics only; therefore the selection of DC reactor value is based on the DC current ripple magnitude generated because of the finite inductance.

It can be shown that at 90° firing angle the ratio of the peak to peak ripple magnitude to rated DC current is

$$I_{RP\%} = \frac{\dfrac{2\sqrt{(2)}V_1 \cos(15^\circ)}{\omega L}\left(1 - \cos\left(\dfrac{\pi}{p}\right)\right)}{I_{DC}} \times 100\% \qquad (3)$$

where p is the pulse number. Since $I_{RMS(F)} = 0.780 I_{DC}$, $p = 12$ and using eqn. 1, the DC reactor inductance for a 12-pulse naturally commutated SVC is

$$L_{12} = \frac{400\sqrt{(6)}\cos(15^\circ)V_1^2}{\omega I_{RP\%}\, 0.780 Q}\left(1 - \cos\left(\frac{\pi}{12}\right)\right) \qquad (4)$$

For the 36-pulse case, since $I_{RMS(F)} = 0.795 I_{DC}$, $p = 36$ and using eqn. 1, then eqn. 3 becomes

$$L_{36} = \frac{400\sqrt{(6)}\cos(15^\circ)V_1^2}{\omega I_{RP\%}\, 0.795 Q}\left(1 - \cos\left(\frac{\pi}{36}\right)\right) \qquad (5)$$

Eqns. 4 and 5 show that the inductance value is inversely proportional to $I_{RP\%}$; therefore, there is a compromise between increasing the inductance to reduce the harmonics, and cost. A ripple level of 10% of the rated DC current (i.e. $I_{RP\%} = 10\%$) was considered acceptable and was used in the design of the experimental model and in the comparison of Table 1. The DC reactor must be rated for the DC current, which is equal to $I_{RMS(F)}/0.780$ and $I_{RMS(F)}/0.795$ for the 12-pulse and 36-pulse, respectively.

In the case of the TCR, reactor impedance is determined by the reactive power rating, i.e.

$$L = \left(\frac{V_1^2}{\omega Q}\right)6 \qquad (6)$$

and their RMS current rating is $I_{RMS}/\sqrt{3}$.

6.4 Reinjection transformers

As shown in Fig. 4, the voltage ripple on the DC side of each 6-pulse convertor is applied to each reinjection transformer and at a maximum at 90° firing angle. This voltage ripple is characterised by $-\sqrt{(2)}V_1 \sin(\omega t)$ for ωt in the range $-(2\pi/12)$ to $+(2\pi/12)$; RMS voltage on the main bridge side of the reinjection transformer is

$$V_{RMS} = V_1\sqrt{\left[1 - \frac{3}{\pi}\sin\left(\frac{\pi}{3}\right)\right]} \qquad (7)$$

The RMS current in the reinjection bridge side of the transformer is $[\sqrt{(2)}I_{DC}]/\sqrt{3}$. Since $I_{RMS(F)} = 0.795 I_{DC}$ and using eqn. 1, the VA rating is

$$S = \left[\frac{0.658}{0.795}\sqrt{\left(\frac{2}{3}\right)} I_{RMS}(F)\right]\left[V_1\sqrt{\left(1 - \frac{3}{\pi}\sin\frac{\pi}{3}\right)}\right]$$
$$= \left(\frac{0.658}{0.795}\frac{\sqrt{2}}{6}\right)\left[\sqrt{\left(1 - \frac{3}{\pi}\sin\frac{\pi}{3}\right)}\right]Q \qquad (8)$$

6.5 Reinjection thyristors

The voltage waveforms on the DC terminals of the individual convertors are $V_a = -\sqrt{(2)}V_1 \sin(\omega t)$ and $V_b = -\sqrt{(2)}V_1 \sin(\omega t + 30)$ and, assuming large blocking capacitors, the commutating voltage of the reinjection bridge is

$$a(V_a - V_b) = a\{\sqrt{[4 - 2\sqrt{(3)}]}V_1 \sin(\omega t - 75^\circ)\} \qquad (9)$$

where a is the reinjection transformer turns ratio (for 36-pulse operation this is 0.658). Therefore, the ideal peak reverse voltage applied to the reinjection bridge (V_{peak}) is $0.658\sqrt{[4 - 2\sqrt{(3)}]}V_1$. The RMS thyristor current is $I_{DC}/\sqrt{3}$, which, in terms of $I_{RMS(F)}$, becomes $1/(0.795\sqrt{3})$ after being normalised. Similarly the average thyristor current $I_{DC}/3$ is normalised to $1/(0.795 \times 3)$.

6.6 Reinjection capacitors

When the reinjection current flows through the capacitors a voltage is generated that has a peak value (V_c) of

$$V_c = \frac{1}{\omega C}\int_0^{\pi/18} aI_{DC}\,d\omega t = \frac{\pi a I_{DC}}{18\omega C} \quad (10)$$

This voltage increases the ideal peak reverse voltage rating of the reinjection bridge, discussed in Section 6.5, by $2aV_c$. The percentage increase ($V\%$) is

$$V_{\%} = \frac{2aV_c}{0.658\sqrt{[4 - 2\sqrt{(3)}]}V_1} \times 100$$

$$= \frac{0.151\left(\frac{I_{DC}}{\omega_C}\right)}{0.48V_1} \times 100\% \quad (11)$$

Since $I_{RMS(F)} = 0.795 I_{DC}$ and using eqn. 1, eqn. 11 can be rewritten in the form

$$C = \left(\frac{Q}{\omega V_1^2}\right)\frac{11.4}{V_{\%}} \quad (12)$$

Eqn. 12 shows that there is an inverse relationship between C and $V_{\%}$; therefore, there is a compromise between reducing capacitance and cost, at the expense of increasing the reinjection bridge rating. A 10% increase of reinjection bridge rating was considered acceptable and was used in the design of the experimental model and in the comparison of Table 1.

7 Conclusions

A new concept of static VAr compensation using naturally commutated thyristor rectification has been described, which operates without the need for active or passive filters. It is based on a combination of high firing angle (close to 90°) and high pulse operation, the latter achieved by means of DC ripple reinjection.

The theoretical waveforms have been verified in a scaled-down model under the control of a digital signal processor. Subject to the limitations of scaling in respect of time constants and magnetisation nonlinearities, the experimental results have clearly shown the ability of the proposed configuration to absorb controllable reactive power while maintaining 36-pulse operation.

While the number and rating of components of the proposed configuration appear to exceed those of the TCR, the comparison is far from straightforward owing to their basic differences in harmonic and dynamic performance. An EMTP model of the proposed configuration is currently being developed to investigate its dynamic response and its behaviour during transient conditions.

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